Grenze International Journal of Engineering and Technology, Jan Issue

Vulnerability Assessment of All Saints' Church - a Unique Heritage Building in Bengaluru

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***Abstract*—Increasing infrastructure projects in mega-cities are leading to greater vulnerability of heritage structures situated in the proximity. Heavy construction activities such as tunnelling, pile driving, deep excavation, movement of heavy vehicles, deep foundation, etc., are common in such projects. A combination of these activities leads to unintended distress in heritage structures, especially unreinforced masonry buildings. It is important to assess the structural health and vulnerability of such buildings. This would help in deciding on conservation strategies, including possible retrofitting of the structure. Bengaluru is one such mega-city which is bestowed with numerous heritage buildings, many of which are in proximity to the on-going metro project. All Saints' church is one such unique single-storied unreinforced masonry building neighbouring one of the underground metro stations proposed. The church was designed by Robert Fellowes Chisholm, a legend in architecture and pioneer of the Indo-Saracenic style, about 150 years ago. Its structural and architectural uniqueness is certainly worthy to be conserved. This paper brings out the details of the attempt made to assess the vulnerability of this structure due to possible lateral loads caused by ground motions induced by construction activities. An investigation has been made to collect the structural details required to model and analyse the structure. An attempt has been made to identify the regions in the load-bearing elements of the building which could experience higher levels of stresses due to lateral loads, using general purpose finite element software. During the study, it is observed that there are certain unique structural elements that have been robustly configured into the architectural features and thus rendered the building healthy despite its age. It is concluded that these unique structural elements need to be carefully monitored and protected to conserve the heritage building.**

***Index Terms*— vulnerability assessment, heritage building, unreinforced masonry, dynamic analysis.**

I. INTRODUCTION

Bengaluru, or Bangalore as it is popularly known, is the capital city of the southern state of Karnataka in India. It is popularly called the "Silicon Valley of India" due to its crucial role in the Indian IT sector and has a metropolitan population of around 110 lakhs. [1] To address the traffic woes of this bustling city, the Bengaluru metro project "Namma Metro" was started in 2011. There is an East-West Corridor which is 18.10km long and a North-South corridor which is 24.20km long in the existing Phase I of the project. In the upcoming Phase – II of Namma Metro, there is an underground tunnel and a station being constructed within 100m of the heritage All Saints' Church. Like most heritage buildings in Bengaluru, this building is also constructed using stone and brick

Grenze ID: 01.GIJET.8.1.16

masonry. The description of this building is provided in the subsequent section.

There are many instances when heavy construction activities in the vicinity of buildings are known to cause distress and generally, the vulnerable buildings/structures are the ones which need protection and mitigation measures. [2] The Ripon Building in Chennai faced severe damage due to close proximity of underground tunnel construction. Cracks could be seen in just about all the structural components. The distress in the structure was the result of deep excavation. Perhaps the extent of damage causing potential was not foreseen and as a result of which, the walls of the masonry building developed huge cracks. [3] On the other hand, there was a concerted effort made to monitor the heritage buildings in the city of Jaipur. A case study has been presented in detail by Shashank Mehendele et al. They report the geotechnical and structural instrumentation for monitoring the activities. It involves instrumentation for measurement of (i) Ground movement in vicinity of the Tunnel Boring Machine (TBM), (ii) Building movement for structures within the zone of influence of the TBM, and (iii) Long term monitoring of the structures even during operations of the metro. Considering the horizontal and vertical alignment of TBMs, the zone of influence was marked from special 3D analysis, carried out for underpass of the tunnels for the entire route under consideration so as to predict the induced surface settlements and angular distortions in the vicinity of the tunnel and thereby, to determine any additional protection measures wherever required. Findings showed that there was no effect of tunnelling beyond 60m of tunnel alignment. Detailed pre-condition and building surveys were carried out for structures along the metro line. Structures were categorized into 3 types - (a) Unstable Structure that needs preventative supports i.e., propping and immediate demolition/evacuation, (b) Part of Structure is unstable and would require propping and partial replacement/demolition, and (c) No major instability noticed, shall need only monitoring. The report discusses the key findings of pre-condition building surveys along with monitoring methods and preventive measures taken before and during construction work of tunnel. Regular and real time monitoring for cracks, settlements, distortion and tilt at critical nodes is also done. Work also extended towards archaeological exploration of the *chaupads* and the careful mapping and reconstruction of the *chaupads*. The primary purpose of geotechnical and structural instrumentation was to monitor the performance of the structures in use, in the vicinity of the underground construction process which also serves a scientific function, or leads to advancement or constant improvisation in design and construction procedures. It can also inform stakeholders and decision-makers in real time if movements or stresses have reached pre-determined trigger levels that demand some kind of mitigative action. All of the monitoring systems including frequency of readings was carefully determined considering the tunnel construction schedule and condition of the structures in vicinity. Equally important is the task to set up standard operating practices (SOP) in case of breach of any alarm or trigger level. They go on to provide a detailed mitigation scheme and the success of implementing the action plan. They conclude that two tunnels were constructed successfully, without touching, repairing most of the more than 2500 structures, including 3 world heritage sites. Few structures required propping and around three structures needed to be reconstructed partly, which became possible because of Structural Health Monitoring (SHM) and continuous monitoring of these structures.

Outside of India, there have been many instances where studies have been done to monitor and conserve heritage masonry buildings that are vulnerable due to tunnelling operations. [4] discusses evaluating the effects of tunnelling on historical buildings in Rome. They present the significant problems connected to buried archaeological remnants, the geotechnical characteristics of the soil, excavation below the water table, and the necessity of minimising the effects on the historical and monumental heritage. They discuss the short-term and long-term effects on built environment due to tunnelling. They adopted 2D and 3D Finite Element Analysis of the structures to understand the effects. [5] discusses the effect of deep excavation and tunnelling works on historical buildings. They state that, as the new desired excavation depth goes deeper than the foundation of the surrounding buildings or when tunnelling works are conducted directly under them, the existing objects are subjected to stress, vibrations and displacements imposed at almost every stage of building the new construction. They also mention the typical damages that appeared in the buildings during the construction of the supporting walls and tunnelling works. The paper highlights the use of finite element analysis to correlate the real-life response.

[6] discusses the holistic approach adopted to conserve the historic Roots Formal Residence (RFR) building during the Wuhan metro construction in China. They have also used Finite Element Analysis to model the building and subject the analytical model to the possible inputs from the tunnelling operations. They conclude that the proposed approach can be used by practitioners in the industry to provide guidelines on the safety management of historical buildings against tunnel-induced damages.

II. Summary

Based on the literature review, it can be stated that there is a need to study, monitor and analyse the historical buildings near the vicinity of metro constructions so as to come out with possible conservation/protection strategies. Finite Element Modelling (FEM) software is a useful tool to model and analyse complex masonry buildings. The FE model could be used to understand the regions that are vulnerable to possible ground motions.

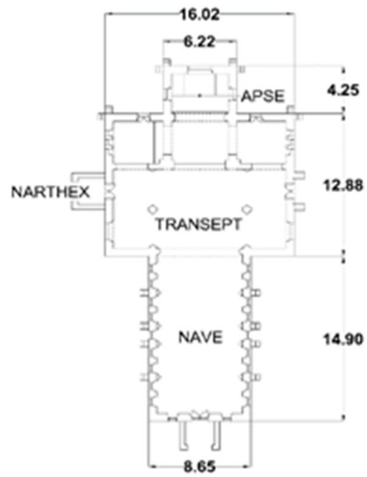

Figure 1. Church Plan with external dimensions in meters

III. Present Study

In the present study, an attempt has been made to understand the vulnerability or otherwise of the heritage All Saints' Church building. Finite Element Analysis is adopted as a tool to model the masonry building. In the absence of the data for the input forces or disturbances on the structure, the vulnerable regions of the structure are understood from the stress-contours and deformation patterns as obtained from the eigenvalue analysis. The influence and importance of some of the critical and interesting structural components are highlighted.

A. Objectives

Broadly, the objectives of the study are stated below;

1. Structural Health Assessment based on detailed visual inspection.
2. To study the possible deformation patterns under dynamic excitations obtained from the mode-shapes.
3. To obtain the stress contours and define the regions of maximum flexural and shear stresses.

B. Configuration

The All Saints' Church follows a Latin Cross or cruciform plan, like many other churches built during that era. It has a nave that runs East-West and transepts that run North-South. The configuration of the building is such that the walls do not run too long before the presence of cross walls, which offer lateral stability. It is a single-storey building with a wall height of 3.47m in the nave portion and 4.26m in the transept and apse portion, and a wall thickness of 0.70m throughout. The church is provided with coursed stone buttresses all along the perimeter to provide lateral support, especially to the long walls of the nave.

C. Structural Elements

The main structural elements of the church include –

1. Masonry: Random rubble masonry has been used on the exterior face of the church. It uses lime mortar and cement pointing. The interior portion was made with burnt brick masonry. A smooth interior finish has been observed. All the openings have rectangular voussoirs around them.

The strength characteristics of the masonry could not be found as this required disturbing the church building. Upon visual inspection, it can be said that the stone used for the construction of the church is Granitoid Gneiss, which is locally available in Bengaluru. [7], [8], [9] Papers whose study was similar to the masonry used in the church were used as a reference. From these papers, a range of values for the compressive strength of Gneiss was obtained which was used to determine the Modulus of Elasticity 'E' value, which was used for analysis purposes. [10] From Clause 7.9.2.1 of IS 1893 Part 1 (2016), the modulus of elasticity for masonry was taken as –

$$E = 550 f_m \qquad (1)$$

Where, f_m is the compressive strength of the masonry prism in MPa.
For analysis, the value of compressive strength, f_m considered, was 33×10^6 N/m^2. Therefore, the value of Modulus of Elasticity, E used for the analysis was 16500×10^6 N/m^2.
2. Foundation: The foundation is constructed in stone masonry with lime mortar. The stones used are presumably roughly dressed granite or gneiss, but it was not possible to excavate and view the exact details. The top, visible portion of the footing is made up of dressed stones.
3. Buttresses: The steep roof held by the trusses exerts a high lateral push, which is counteracted by the buttresses provided all along the building. Atotal of four pairs of buttresses are provided for each of the trusses on both sides of the nave. Two pairs are provided on the far corner of the transept and two on the apse. The buttresses are composed of coursed stone masonry in lime mortar. The joints are covered with cement pointing. The buttresses in the nave are 2.18m in height and those in the transept and apse are 4.26m.

Figure 2. Buttresses in Nave

4. Roofing System and trusses: A Gothic-style crossed-gable/crossed-A frame roof has been adapted in All Saints' Church. The transept portion consists of two gables and a Madras Terrace. Two layers of Mangalore tile cover the roof. The roof starts from the nave wall at a mere height of 3.47m. It makes an angle of 53° to the horizontal. The inner height from the bottom surface to the ridge beam is 8.20m. Four purlins on both sides run along the length of the nave. Two dormer windows are present on either side of the nave roof. The two gables in the transept resemble the letter 'M'. The angle of the roof is 65° to the surface and the height of the ridge beam is 7.55m.

Figure 3. All Saints' Church

A total of 6 wooden trusses are used in the nave portion - 3 scissor trusses and 3 king-post with an arch brace below the tie-beam. The spacing of the trusses is not uniform. All the trusses are embedded in the stone pillars protruding from the wall. Cleat angles with nuts and bolts are used to connect the truss and the wooden elements. The actual extent to which the trusses were embedded in the pillars was unknowable.
5. Arches: There are a total of 8 pointed arches, all of which are in the transept. All the arches are made of brick masonry. Four of these arches are located near the entrance through the side doors, all of which have a height of 5.0m and a width of 3.2m at the springer. These four arches are supported by vertical supports on both sides.

Three of the remaining arches are located at the altar of which two arches have a height of 4.96m while the other arch running east-west has a height of 4.78m. The last arch is present at the junction of the transept and apse and has a height of 4.52m. These four arches are not supported by vertical supports.
6. Pillars: The pillars sit under beams and arches and transmit the weight of the structure above to the other structural elements below it. There are four quatrefoil pillars that serve as vertical supports for the pointed arches at the transept. Two of these pillars are embedded in the wall. All the circular pillars are implanted in the wall and have king post trusses and scissor trusses embedded in them. All pillars have a height of 2.25m. The circular pillars have a diameter of 0.55m.

D. Architectural Details

The All Saints' church was designed by renowned British architect, Robert Fellowes Chisholm. It follows the Indo-Saracenic architectural style with many Gothic elements as well. The tiled roofs which are very steeply sloped and the random rubble masonry walls are unique features of the church. The Gothic style is exemplified by the use of narrow and tall pointed arch windows, stone voussoirs, and dormer windows in the gable roofs. The scissor trusses and king-post trusses with arched braces commence at a height of 2.2m, which is rather unusual. There are stained glass windows above the doors and behind the altar. Like most Anglican churches, the walls are adorned with memorial plaques commemorating the service of those in the military as well as other important positions.

IV. Finite Element Analysis & Modelling

Finite Element Analysis was used to assess the vulnerability of the building. Eigen analysis delivers eigenvalues which represents natural frequencies and eigenvectors corresponding to the mode shapes. NISA (Numerically Integrated elements for System Analysis) was a general-purpose software used for the analysis. The modal analyses provided the area of the vulnerable regions and the stress contours presented the extent of vulnerability. Few assumptions were made during the modelling process -
(i) The short wall of the nave is of the same height as the long wall of the nave. [11] As a circular opening is present on the short wall, the top triangular portion above 3.47m does not contribute to the load-carrying of the truss as per the national building code.
(ii) The narthex walls act as buttresses.
(iii) The buttresses are embedded in the walls and hold the trusses' lateral thrust.
(iv) The rear end of the apse is of the same height as the transept.
(v) Arches linking the internal columns acts as beams
A least count of 0.4m was chosen for simplified modelling which still accurately depicted the behaviour of the building. After modelling the walls and buttresses, discretization of the elements was done. This process was done to individual structural elements which made node management easier in such a way that the nodes on the buttresses were aligned to the nodes on the wall. It ensures that the structure act as a whole and not as individual elements.

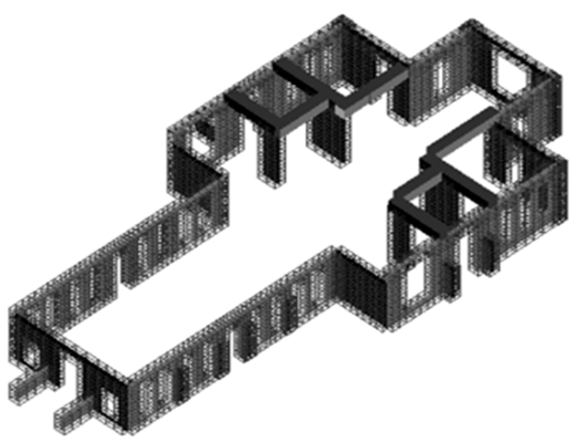

Figure 4. 3D view of the modelled plan in NISA

TABLE I. MODELLING EQUIVALENTS FOR DIFFERENT STRUCTURAL ELEMENTS

Structural Elements	Modelling equivalent	Remarks
Walls and buttresses	2D Shell elements	Walls were divided into smaller parts with a least count of 0.4m
Arches	3D beam	These were used instead of arches so that the internal columns did not act as free-standing columns
Openings	Absence of nodes	Wall was modelled in such a way that the openings were separated initially
Trusses	Restraints	Boundary condition was used on top of the wall above the buttresses to mimic the trusses' action. Translation was allowed while rotation was restricted
Foundation	Displacement restraints	Both the rotational and the translational movements were restricted

The analyses were done an increasing level of complexity and the results are presented in Table II.

The level 1 analysis was done taking into account only the walls without any openings or slab elements. It was observed that the breathing mode of vibration was dominant in the earlier natural frequencies. However, the vibration was often concentrated in specific wall elements and not common to the entire structure.

The level 2 analysis exhibited the importance of the buttresses in terms of the stiffness they provided, especially to the walls of the nave. The analysis presented that the deformations in the left transept wall were slightly larger than those in the right transept wall, possibly due to the greater stiffness provided by the buttresses on the right wall compared to those on the left wall.

In level 3, the structure was modelled taking into account the walls, buttresses, and internal columns. As the top of the structure was not tied together by a roof in the analysis, in order to prevent the internal columns from acting as free-standing columns, the columns were tied together and to the neighbouring walls. It was observed that the fundamental mode shapes shifted to the nave portion. In the transept, the addition of internal columns and their connections resulted in the vibrations spreading to the cross walls as well.

Compared to the previous level of analysis, after adding restraints in level 4, especially at the truss locations, it was observed that the fundamental mode shape moved from the long walls of the nave to the cross wall of the nave. The fundamental natural frequency was highest at this level. This increase in stiffness can be attributed to the addition of restraints.

Level 5 was the most detailed and closest to the actual structure in all the analyses. It was seen that the fundamental mode shapes shifted to the nave portion. In the transept, the addition of internal columns and their connections resulted in the vibrations spreading to the cross walls as well.

To identify the extent of vulnerability, stress contours were required. [9] A ground acceleration of 0.2g or 1.96 m/s^2 was applied which is higher than the specified zone factor of 0.1g for regions in Seismic Zone II as per Table 2, Annex E, IS 1893 (Part 1). The value taken is such that most TBM ground accelerations fall within it. The ground acceleration was applied in two directions along the X and Y axes. The results are presented in Table III.

V. RESULTS

TABLE II. NATURAL FREQUENCY RANGE FOR DIFFERENT LEVELS OF COMPLEXITY

Levels	Elements Modelled	Natural frequency range (Hz)
Level 1	Solid walls	21.03 – 42.04
Level 2	Solid walls + buttresses	23.21 – 43.01
Level 3	Solid walls + buttresses + internal columns	27.20 – 44.23
Level 4	Solid walls + buttresses + internal columns + restraints	41.24 – 64.70
Level 5	Solid walls + buttresses + internal columns + restraints + openings	37.44 – 66.90

A. Comparative Analyses

The study was not only limited to the complexity of the building. Comparative analyses were performed to understand the influence of different elements.

Changing the modulus of elasticity (E) does not seem to influence the mode shape. As expected, the natural frequency increased when the value of 'E' was raised and decreased when 'E' was decreased. After removing the buttresses from the final level of analysis, it was seen that the frequency has reduced slightly, possibly due to the decrease in stiffness. Although the mode shapes remained the same at the fundamental mode and a few subsequent modes, they have changed at higher modes.

The natural frequencies reduced greatly when the restraints at the top edge were removed. This indicated that these restraints provided a great deal of stiffness. Further, this means that the trusses and their possible deterioration could be a great cause for concern.

When the columns were removed, the transept portion became increasingly vulnerable and dominated the first two mode shapes. The fundamental natural frequency decreased without the columns, which is expected, given the reduction in stiffness.

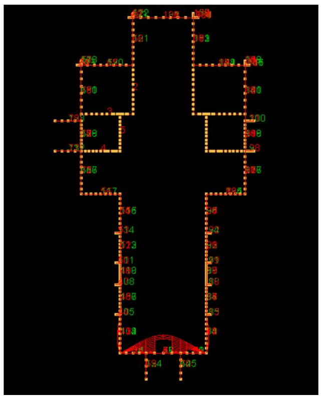

Figure 5. Fundamental Mode of Level 5 analysis

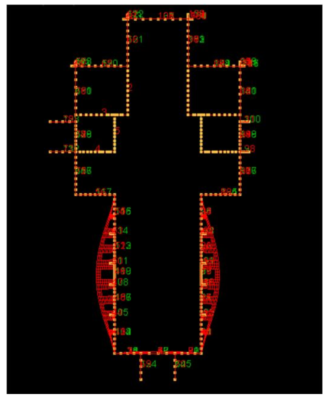

Figure 6. Fundamental Mode after removal of restraints

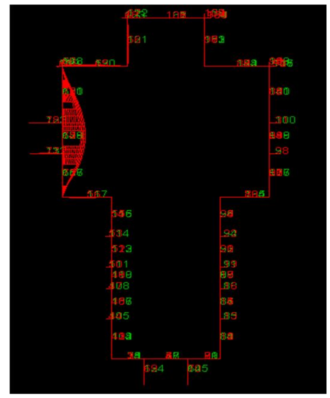

Figure 7. Fundamental Mode after removal of Internal Columns

The maximum flexural stresses in the vulnerable regions as obtained from the stress analysis performed by applying a uniform lateral acceleration of 0.2g is presented in Table III. It can be seen that the maximum extreme fiber stress developed is 0.121MPa. This is limited to a small region at the corners and junctions. The masonry is capable of withstanding this level of stress. It was noted that the shear stresses were marginal, expectedly, due to the adequate shear resistance by way of wall thickness and the presence of a large footprint of shear walls in both directions.

TABLE III. STRESS IN XX AND YY PLANE

Direction of ground motion	s_{xx} (MPa)	s_{yy} (MPa)
X - direction	0.094	0.064
Y - direction	0.120	0.121

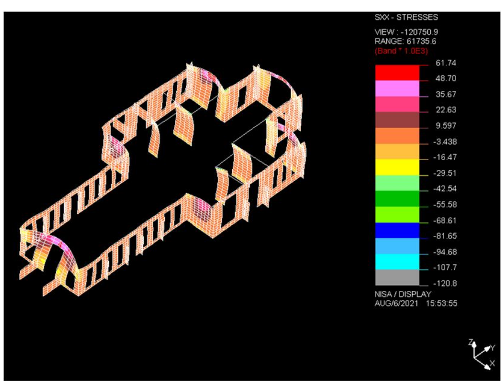

Figure 8. Stress Contour (s_{xx}) due to acceleration in y-direction

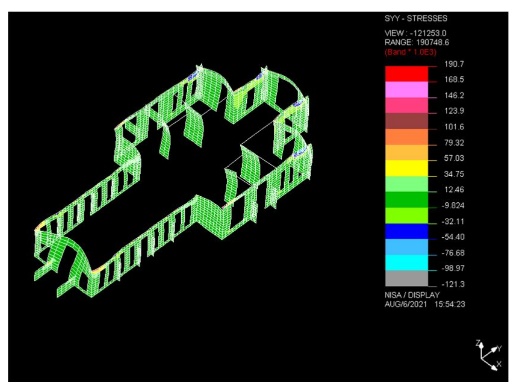

Figure 9. Stress Contour (s_{yy}) due to acceleration in y-direction

VI. CRITICAL OBSERVATIONS

As stated earlier, eigenvalue analysis was carried out to obtain the natural frequencies and the corresponding mode shapes. The mode shapes, especially the fundamental mode gives an insight into how the building would respond in the event of dynamic inputs. It is well-known that when a natural frequency matches with the input frequency, the response gets amplified. Generally, much of the contribution is from the fundamental mode, and hence, as a first step towards identifying the vulnerable regions, the fundamental mode shape and the modal stress can be considered.

The building possesses a complex plan configuration. There is no global mode of deformation such as a dominant sway mode in either of the horizontal axis. It is the individual walls which are contributing to the flexural mode of deformations. Therefore, it is crucial to understand how these walls would perform when the critical restraints are released. For instance, with the release of the restraint at the top edge (meaning the truss-wall junction has given way), the long walls suddenly experience more out-of-plane flexure dominant deformation and thus would become vulnerable. Likewise, there are a number of such critical elements in the building which are preventing excessive deformations and contributing to the overall robustness. They are:

(i) the connection between the trusses and the wall and the walls at these junctions are thickened by the pillars.

(ii) buttresses adjoining the long walls adding to the lateral stability.

(iii) the four internal columns in the transept support the arches and they, in turn, are connected to the outer walls which contribute to the stability of the outer walls of the transept.

(iv) openings in the long walls are quite narrow and thus the reduction in stiffness is only marginal.

VII. Concluding Remarks

The historic All Saints' church is uniquely configured by several interesting structural elements and these are not only enhancing the architectural beauty but also contributing to the overall robustness of the unreinforced stone masonry building. The fundamental frequency indicates that the structure is relatively stiff. The analysis revealed that these elements dictate the mode of deformation and have helped in relieving the flexural and shear stresses in the load-bearing walls. The detailed visual inspection indicated that no portion of the building is under distress. However, it is imperative that the wall-truss junction, the buttresses, the masonry columns supporting the arches in the transept, and the vertical edges of the walls be monitored on a continual basis. Any distress developed in these elements would render the building vulnerable to dynamic inputs and/or ground settlement. There is a need to develop a protocol to monitor the structural health of the building. One relatively easy way would be to recurrently measure the fundamental natural frequency through the response from free-vibration studies and keep a track of the reduction in the frequency. Any significant reduction in the frequency is an indication that the stiffness is degrading and calls for detailed monitoring of the key elements. It is also important to develop a comprehensive conservation protocol as per the heritage conservation norms.

Acknowledgement

We would like to thank those in charge at All Saints' Church, especially Rev. Satish Timothy Paul for allowing us to carry out our visual studies at the site and obliging with our requests. We would also like to extend our gratitude to Shibani S., Smrithi M P and Tejaswini S Murthy, who helped us constantly with their valuable inputs and feedbacks.

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